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Methods for saturated soil hydraulic conductivity determination in different soils

Rafael Dreux Miranda Fernandes[1], José Geanini Peres[2], Jefferson Vieira José[3], Sérgio Nascimento Duarte[3], José Antônio Frizzone[3]

[1] Departamento de Cristalografía, Mineralogía y Química Agrícola, Facultad de Química, Universidad de Sevilla; rafadreux@gmail.com
[2] Departamento de Recursos Naturais e Proteção ao meio Ambiente, Universidade Federal de São Carlos
[3] Departamento de Engenharia de Biossistemas, Universidade de São Paulo

Abstract: The article describes a study about the differences between three methods used to measure saturated soil hydraulic conductivity (K_0) in four sites with different textural classes and soil managements. The completely randomized statistical design was used in a 3 x 4 factorial scheme, with four replicates. The three methods used were: (i) constant head permeameter with soil samples of undisturbed structure (USS), (ii) constant head permeameter with soil samples of disturbed structure (DSS) and (iii) Guelph permeameter (GP). The four sites in which the methods were performed were: clay soil in fallow (CSF); clay-sandy soil under virgin forest (CSVF); clay soil under sugar-cane crop (CSC); and sandy loam soil under horticulture (SLH). At the same time, measurements with the GP method, varying the water head from 0.02 to 0.16 m, were performed in eight replicates. In the sites with soils with higher clay content (CSF and CSC), there was significant difference between GP and the other two methods, allowing the use of DSS, since there was no significant difference between this method and USS. In the sites with lower clay content (CSVF and SLH), however, there was significant difference between the three methods; DSS overestimated K_0 and PG underestimated K_0 when USS is taken as the standard method. When comparing the different water heads used in the GP method, no significant difference was detected between them.

Keywords: constant head permeameter, undisturbed soil sample, Guelph permeameter.

Métodos de determinação da condutividade hidráulica do solo saturado em diferentes solos

Resumo: O trabalho objetivou estudar as diferenças entre três métodos de medição da condutividade hidráulica do solo saturado (K_0) em quatro locais com diferentes classes texturais e usos do solo. O delineamento utilizado foi inteiramente casualizado arranjado em um fatorial 3x4, em quatro repetições. Os três métodos utilizados foram, (i) o permeâmetro de carga constante com amostras de solo com estrutura indeformada (AI), (ii) o permeâmetro de carga constante com amostras de solo com estrutura deformada (AD) e (iii) o permeâmetro de Guelph (PG). Os quatro locais nos quais os métodos foram aplicados foram: solo argiloso em pousio (AP); solo argilo arenoso sob mata virgem (AAMV); solo argiloso com cana de açúcar (AC); e solo franco arenoso sob culturas de hortaliças (AFH). Paralelamente, realizaram-se medições com o PG variando-se a carga hidráulica de 0,02 a 0,16 m, em oito repetições. Nos locais com solo com alto teor de argila (AP e AC) houve diferença significativa entre o PG e os outros dois métodos, podendo-se utilizar AD, já que não houve diferença significativa entre este e o AI. Já nos locais com menor teor de argila (AAMV e AFH), houve diferença significativa entre os três métodos, sendo que AD superestimou K_0 e PG subestimou K_0 quando se toma AI como padrão. Quanto à comparação entre as cargas hidráulicas utilizadas no PG, não houve diferença significativa entre estas.

Palavras-chave: permeâmetro de carga constante, amostra de solo com estrutura indeformada, permeâmetro de Guelph.

Introduction

The hydraulic conductivity is a physical parameter of soil that quantifies the speed with which the soil conducts liquids. For the water, it depends on the soil water content, because the higher its content, the higher the flow section will be. Thus, the soil hydraulic conductivity has its maximum value when the soil is saturated (Carvalho, 2002).

The knowledge about the hydraulic conductivity is important for different areas of research as for the characterization of the solutes transportation in the soil profile, to project and manage irrigation and drainage systems, canals and reservoirs, and for many agricultural, industrial and environmental infra-structures (Lee et al., 1985).

The soil hydraulic conductivity (K), informs about the soil transportation capacity of water, solutes and chemical substances. It is the main physical attribute of the soil, because it influences the infiltrating process of water in the soil, irrigation and drainage projects, the loss of fertilizers by soil erosion and the percolation of substances by leaching; consequently it is the parameter that influences all the process of soil and water management (Mesquita & Moraes, 2004).

According to Dalbianco (2009), despite the great variability of K_0 between samples, it has been used to characterize the soil structural quality, being analyzed together with other soil physic and hydraulic attributes.

According to Mesquita & Moraes (2004), K_0 can be determined by indirect methods, through the use of mathematical relations and correlations between K_0 and other non-hydraulic variables of the soil, as soil density, soil total porosity, macro and micro porosity, which influences the pores distribution and therefore the soil permeability.

There are different methods for K_0 determination, some are performed in the field and others in laboratory. Some methods are easier to perform than others, e.g. to obtain undisturbed soil samples is more laborious than to obtain disturbed soil samples for K_0 determination when using the constant head permeameter.

Another example would be the use of Guelph permeameter (in the field), which does not requires soil samples for the determination of K_0; this is a less laborious method than taking samples (disturbed or undisturbed) to be used in a constant head permeameter in a laboratory.

According to Scherpinski et al. (2010), the Guelph permeameter is used to measure, in the absence of shallow water table to a depth of two meters, of field saturated soil hydraulic conductivity (K_{fs}), the matrix flux potential (φ_m) and the soil sorptivity (S).

Considering these facts, the hypothesis of this study was that there are alternative and less laborious methods to measure K_0 with similar results of the standard method of constant head permeameter with a soil sample of undisturbed structure. To verify the hypothesis, the objective of the present research was to compare three methods used to determine hydraulic conductivity of saturated soil in four sites with different textural classes and soil management. At the same time, it aimed to compare the values of K_{fs} obtained by the use of different water heads in the Guelph permeameter method, in just one of the four sites.

Material and Methods

A completely randomized statistical design was used in a factorial setting of 3x4, where three methods were used to measure K_0 in four sites, with four repetitions. The methods were: (*i*) constant head permeameter with soil samples of undisturbed structure (USS), (*ii*) constant head permeameter with soil samples of disturbed structure (DSS) and (*iii*) Guelph permeameter (GP). The chosen sites had soils with different textural classes and different vegetal cover or soil management, which were: clay soil in fallow (CSF); clay-sandy soil under virgin forest (CSVF); clay soil under sugar cane crop (CSC); and sandy loam soil under horticulture (SLH).

The CSF site did not presented vegetal coverage and its soil was not tilled in years before these experiments. The CSVF site presented semideciduous seasonal forest as vegetal cover. The CSC site had its soil extremely explored by sugar cane production. These three sites are located in the county of Araras – SP, in the Centro de Ciências Agrárias of Universidade Federal de São Carlos (UFSCar). The SLH site has its soil managed for agriculture, and is located inside of a greenhouse cultivated for horticultural production, in the county of Monte Alto – SP.

The soil bulk density (ρ_b), the soil particle density (ρ_s) and the textural classes were determined according to the methods proposed by EMBRAPA (1997), for the soil layer of 0.0 to 0.2 m. The physical characteristics of the soils of each site are presented in Table 1.

The undisturbed soil samples, for the measurement of K_0 were obtained by metal rings of 275 cm^3 of volume, which were introduced in the layer of soil from 0.00 to 0.20 m of depth, using two rings: one with beveled base and the other, above the first, only to be hammered for the gradual introduction of the first ring into the soil. The undisturbed samples were then taken to the laboratory, where the exceeding soil was

Table 1. Soil physic characteristics from the four studied sites

	ρ_b	ρ_s	Clay	Sand	Silt	Textural classes
	kg m^{-3}		%			
CSF	1250	3050	57	20	23	Clay
CSVF	1140	2950	37	49	14	Clay sandy
CSC	1216	2960	63	18	19	Clay
SLH	1476	2700	14	85	1	Sandy loam

CSF – clay soil in fallow; CSVF – clay sandy soil under virgin forest; CSC – clay soil with sugar cane crop; SLH – sandy loam soil under horticulture; ρ_b –soil bulk density; ρ_s – soil particles density.

removed. Following that, a porous cloth was placed on the bottom face of the soil column, held by a rubber band. These metal rings with the soil samples and the porous cloth were placed on a plastic tray with distilled water, aiming to saturate the soil columns by capillary rise.

The disturbed soil samples, also for the measurement of K_0, were obtained from quantities of oven-dry soil (ODS), obtained as described in EMBRAPA (1997), with soil of each one of the four sites, taken from the layer of 0.00 to 0.20 m of depth. This mass of ODS was calculated so that the soil bulk density in the metal rings would be similar to the soil bulk density at natural conditions for each site (Table 1). So, the accommodation of ODS inside the metal rings is similar to those used for the undisturbed soil samples. In these rings, the same kind of porous cloth was used to hold the soil during accommodation and measuring procedures. The ODS was compressed into the metal rings to obtain the desired soil bulk density. These rings with disturbed soil samples were then placed in plastic trays with water for soil saturation.

Both the rings with undisturbed soil samples and those with disturbed soil samples were used for the measurement of the hydraulic conductivity of saturated soil (K_0) with the use of the constant head permeameter, which maintains a constant water head over the columns of soil during the water percolation. For that, it is necessary to measure the water head above each ring, because this value varies between each ring and it is required for the calculation of K_0. The measurement of K_0 was performed accounting the volume of water that flows through the soil in a certain period of time, in function of the water head and of the column height and section area. These measurements were performed repeatedly, until equal volumes in three consecutive repetitions were obtained and therefore determining the hydraulic conductivity of the saturated soil.

The measurements using the method of Guelph permeameter were performed according to the descriptions made by Soilmoisture (2010) and Kodešová et al. (2011). A water head of 0.05 m was used and, for each measurement a hole with a diameter of 0.05m and 0.10 m of depth was opened in the soil using an auger hole.

Eight water heads (h) were also compared with the GP method. The water heads studied were respectively 0.02, 0.04, 0.06, 0.08, 0.10, 0.12, 0.14 and 0.16 m. Each water head was used in eight repetitions (holes in the soil). These holes had 0.05 m of diameter and 0.20 m of depth, opened with assistance of an auger hole. The measurements of K_{fs}, in this case, were performed in sequence, i.e. only after finishing the measurements with the eight water heads in one hole, the measurements in the next hole were started. Usually three to four measurements were performed consecutively, using water heads in an ascending order. This experiment was performed only in the first site mentioned before (CSF), to make it possible to compare the obtained results.

The soil's hydraulic conductivity data were analyzed for the tendency to normality, by the test of Shapiro-Wilk, and for the homogeneity of variances, using the test of Bartlett. When results of p-value for these tests were below 0.01 (1% of significance), the test of Box-Cox was used to obtain the most adequate transformation for the data to present homogeneity of variances and tendency to normality. These data were submitted to the analysis of variance, and after that to the Tukey test of averages. The data regarding the comparison between methods and sites and the comparison of water heads in the Guelph permeameter were analyzed separately.

Results and Discussion

From the data regarding hydraulic conductivity obtained in the four sites by the three mentioned methods, the tests of Shapiro-Wilk and of Bartlett were performed, with the need to use the Box-Cox test to identify the best transformation to be used, to obtain data with homogeneity of variances and tendency to the normality. A value of lambda (λ) equal to 0.2 was obtained, with which, after transformation, was possible to obtain p-values for the tests of Shapiro-Wilk and Bartlett higher than 0.01, allowing to proceed with the analysis of variance. The analysis of variance conducted according to the factorial setting (methods x sites) provided the results presented in Table 2.

Observing Table 2, it is possible to verify that there was significant difference (at 1% of significance) between the sites and between the methods, as well as for the interaction between methods and sites. Consequently, the Tukey test can be applied only between the sites within each method and between the methods within each site (Table 3).

Table 2. Analysis of variance of the hydraulic conductivity data according to the factorial setting

	DF	SS	MS	F	p-value
Methods (M)	2	64.07	32.04	86.78	$1.70\ 10^{-14}$ **
Sites (S)	3	17.09	5.70	15.43	$1.29\ 10^{-6}$ **
Interaction M x S	6	21.13	3.52	9.54	$2.78\ 10^{-6}$ **
(Treatments)	(11)	(102.30)	(9.30)	(25.50)	$(1.17\ 10^{-13})$ **
Residuals	36	13.29	0.37		

DF – degrees of freedom; SS – sum of squares; MS – mean squares. Significance levels: ** - p-value < 0.01; * - p-value < 0.05; NS - p-value > 0.05

Table 3. Hydraulic conductivity averages (m d^{-1}) obtained by the three methods in the four sites

Methods	Sites			
	CSF	CSVF	CSC	SLH
DSS	2.527 aC	23.018 aB	2.086 aC	7.106 aA
USS	2.857 aAB	6.449 bA	1.935 aB	2.022 bB
GP	1.034 bA	0.378 cA	0.583 bA	0.532 cA

According to the Tukey test, different letters mean that there is significant difference (5% of significance), being lowercase in the columns and uppercase in the lines; CSF – clay soil in fallow; CSVF – clay sandy soil under virgin forest; CSC – clay soil with sugar cane crop; SLH – sandy loam soil under horticulture; DSS – constant head permeameter with disturbed soil samples; USS – constant head permeameter with undisturbed soil samples; GP – Guelph permeameter.

The data of K_0 in CSF and CSC presented a significant difference at 5%, between GP and the other two methods. On the other hand, the data of K_0 in CSVF and SLH presented significant difference at 5% between the three methods. So, establishing USS as the pattern method, it is possible to state that in the sites with higher clay content (CSF and CSC), DSS can be used safely, obtaining data of K_0 similar to those obtained by USS. However, for the sites with soils with lower clay content (CSVF and SLH), the results suggest that DSS overestimated K_0 and GP underestimated K_0.

Regarding the data of soil hydraulic conductivity obtained with DSS, there was only significant difference between the site SLH and the other sites and between CSVF and the other sites; however there was no significant difference between CSF and CSC. Regarding the method of USS, the site CSVF presented significant difference (at 5% of significance) in comparison to the sites CSC and SLH, but the site CSF did not presented significant difference in comparison to the other sites. On the other hand, the GP method did not identify significant differences (at 5% of significance) between the four studied sites.

Comparing the results of the methods USS and DSS for the four sites, and the results of the three methods for the same sites, it is possible to state that the DSS methodology worked better for soils with higher clay content (CSF and CSC) than for the soils with lower clay content (CSVF and SLH). Therefore, it is possible to state that the methodology of resembling the soil with its original bulk density does not work for soils with lower clay content and higher sand content, as well as it does for the soils with higher clay content.

It is important to highlight that the measurements of K_0 using GP were performed with field saturated soil, which might not have occurred completely, i.e. in this method the soil saturation process is done from above to bellow and it allows for the possibility that some air had gotten retained in some micropores (Soilmoisture, 2010).

Rossi et al. (2007) obtained, for clay texture soil, values of K_0 of 0,985 and 0,408 m d^{-1}, using disturbed and undisturbed soil samples, respectively. One possible explanation for the difference between the values of K_0 in the mentioned article and in the present study may be related to the difference in the soil bulk density, which is higher in the soils of the study of Rossi et al. (2007).

In a soil of medium texture (68% of sand and 21.8% of clay), these same authors obtained values of K_0 of 4.536 and 0.595 m d^{-1}, with undisturbed and disturbed soil samples, respectively. Despite the clay and sand content being different, these values are similar to the values obtained in the site SLH. The difference between the values of K_0 obtained in these two studies can be explained by the different contents of particles of different sizes, as mentioned above.

Through the analysis of other studies (Marques et al., 2008; Silva et al., 2006; Torres et al., 2011) that used undisturbed soil samples in the constant head permeameter, it is possible to verify that the values of K_0 change drastically according to the soil bulk density.

For example, in the experiment performed by Torres et al. (2011), the values of K_0 obtained in an area with conventional tillage system were smaller than the average K_0 obtained in the site CSC. However, the soil of the mentioned study presented a soil bulk density of 1480 kg m^{-3} larger than the ρ_b of the soil of the site CSC. However other aspects that influence the value of K_0 , as the presence of roots and the organic matter content should be considered.

Analyzing other studies that used the Guelph permeameter for the measurements of K_{fs} (Eguchi et al., 2003; Souza & Alves, 2003; Assis & Lanças, 2005; Kodešová et al., 2011), it is possible to observe that the results obtained in the CSC site are similar to those obtained in the mentioned articles, in which K_0 varied from 0.130 to 2.16 m d^{-1} in cultivated soils. So, it is observed that the average value obtained with the GP method in the CSC site is within this interval of K_0.

The data of soil's hydraulic conductivity obtained with the use of different water heads in the Guelph permeameter method were submitted to the tests of Shapiro-Wilk and of Bartlett, obtaining results of p-value equal to 2.62 10^{-5} and 0.526, respectively. These data, then, were submitted to the test of Box-Cox for the transformation, obtaining a lambda value (λ) equal to 0; meaning that the best transformation method was to apply logarithmic to the original data. After the transformation, the results of p-value for the tests of Shapiro-Wilk and of Bartlett were 0.473 and 0.991, respectively. In Table 4 the results of the analysis of variance of the data of K_{fs} obtained with the use of different water heads in the Guelph permeameter are presented.

It is possible to verify, according to the analysis of variance presented in Table 4, that the F-test revealed that there was statistical difference, at 1% of significance, between the holes in the soil and, at 5% of significance, between the studied water heads. There was also significant difference between the water heads expressed as a quantitative variable. Therefore, it was possible to perform the regression analysis. The results of the analysis of variance of the linear and quadratic regression models are presented in Table 5.

Observing Table 5 it is possible to verify that none of the regression models was capable to explain the differences between the data of K_{fs} obtained with the studied water heads. As an option, an average test was performed, using the Tukey test, with the values of K_{fs} obtained with the different water heads in the eight repetitions, whose results are presented in Table 6.

It is possible to verify, through the observation of Table 6, that the values of K_{fs} obtained with the different water heads did not presented significant differences (at 5% of significance); but, the average values of K_0 differed significantly between the holes, revealing a high spatial variability of K_{fs}.

Table 4. Analysis of variance of the data of field saturated soil's hydraulic conductivity (K_{fs}) obtained with the use of different water heads in the Guelph permeameter

	DF	SS	MS	F	p-value	
Water heads	7	0.425	0.061	2.322	0.040	*
Repetitions	7	3.562	0.509	19.476	3.57 10^{-12}	**
Residuals	49	1.280	0.026			

DF – degrees of freedom; SS – sum of squares; MS – mean squares. Significance levels: ** - p-value < 0.01; * - p-value < 0.05; NS - p-value > 0.05.

Table 5. Analysis of variance of the linear and quadratic regression models of field saturated soil hydraulic conductivity in function of different water heads in the Guelph permeameter

	DF	SS	MS	F	p-value	
Linear	1	0.228	0.228	2.798	0.0996	NS
Quadratic	1	0.025	0.025	0.301	0.5851	NS
Residuals	60	4.883	0.081			

DF – degrees of freedom; SS – sum of squares; MS – mean squares. Significance levels: ** - p-value < 0.01; * - p-value < 0.05; NS - p-value > 0.05.

Table 6. Tukey test's results for the data of hydraulic conductivity (m d^{-1}) obtained with the use of different water heads in eight holes

h (m)	K_{fs} (m dia^{-1})	Holes	K_{fs} (m dia^{-1})
0.02	0.555 a	1	0.269 bcd
0.04	0.532 a	2	0.252 cd
0.06	0.564 a	3	0.894 a
0.08	0.511 a	4	0.904 a
0.10	0.404 a	5	0.223 d
0.12	0.343 a	6	0.301 bcd
0.14	0.358 a	7	0.422 bc
0.16	0.421 a	8	0.426 b

By the Tukey test, different letters mean that there is a significant difference (5% of significance); h – water head; K_{fs} – field saturated soil hydraulic conductivity.

Although the results of ANOVA reveal that there is significant difference between the water heads used in the GP method, the results of the Tukey test (Table 6) revealed that the differences are not significant. This result confirms that the equation for the estimative of K_{fs} by the GP method takes into account the water head used, so there is no need to establish a fixed water head for different measurements. The differences between the tests are relatively common, because, usually, the F-test is more sensible than the Tukey test.

Elrick et al. (1989) compared water heads between 0.05 and 0.125 m, varying each 0.025 m, and found a small variation between the average values obtained for each water head; the highest value of K_{fs} was obtained with the water head of 0.10 m (3.197 m d^{-1}), and the smallest value was obtained with a water head of 0.05 m (2.506 m d^{-1}).

Conclusion

In the soils with higher clay content the values of K_0 obtained with the method of constant head permeameter with disturbed soil samples can be used, once they are similar to those obtained with the constant head permeameter with undisturbed soil samples. However, in these same sites, the Guelph permeameter underestimated the measurements of K_0.

In the soils with lower clay content, the method of constant head permeameter with disturbed soil samples overestimated K_0 and the method of Guelph permeameter underestimated K_0, considering the method of constant head permeameter with undisturbed soil samples as the standard method.

There was no difference between the studied water heads when measuring the soil hydraulic conductivity with the Guelph permeameter method.

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